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Abstract

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Nomenclature

S_{gen}	entropy generation
S_dot	entropy generation rate
Q	amount of heat transfer
Q_dot	heat transfer rate
dS	entropy change
L	length of the heat exchanger
U	velocity of the fluid
D_h	hydraulic diameter
K_s	relative roughness of the shell or tube material
Re_D	Renold number
f	friction coefficient
ρ	density
α,β	factors to compute friction coefficient
∇P	pressure drop

m_dot	mass flow rate
dp	pressure drop
dx	unit length
T_{ln}	log mean temperature of single-phase flow
C_p	specific heat
R	general gas constant
Q_L	amount of heat at low temperature
Q_h	amount of heat at high temperature
q'	heat flux
S_t	Stanton number
S_p	total entropy in the products of a combustion process
S_r	total entropy in the reactants of a combustion process
$S_{thermal}$	entropy generation due to energy conversion
S_{manu}	entropy generation in manufacturing process due to energy conversion
N	number of the tubes in a heat exchanger

Chapter 1. Introduction

1.1 Second law analysis of thermal systems

The heat exchange process, whether performed in a single heat exchanger or a complex system of heat exchangers, represents an important step in energy conversion and use. This is true in industrial applications, power generation systems, transportation systems, residential and commercial heating and cooling applications.

The design of thermal energy systems has been historically based on the first law of thermodynamics, that is, maximizing energy transfer. The introduction of the second law analysis of the thermal system is to comprehensively understand the true source of inefficiency of the system. The second law analysis can be used to optimize the thermal system. In this case, the total entropy generation from the entire industry process should be minimized. This method is expected to reflect the entire effort expended to produce and operate a thermal system. It is important for the designer to master this method.

1.2 Background

The first paper on the minimization of entropy generation in heat exchangers was written by MCClintock.(1951). In 1982, professor London published his first paper on entropy generation minimization in heat exchangers (Bejan, 1996).

Bejan (1982) studied extensively the optimization of a heat exchanger, excluding entropy generation associated with use of materials and the generation of heat and power. His approach uses the concept of entropy generation minimization. An extension to his

approach to include material use has been made by Aceves and Saborio et al. (1989). They took into account the irreversibility associated wwith the use of the materials, but did not include the irreversibility due to pressur drops.

Tondeur and Kvaalen (1987) have shown that in the case of heat exchangers or separation devices involving a given heat transfer and achieving a specified transfer duty, the total entropy produced is minimized when the local rate of entropy production is uniformly distributed along space variables and time.

De Oliveira et al. (1994) have shown that in the case of an optimal heat exchanger the thermal and viscous contributions to the entropy generation should be equal when the heat flux is optimized. The ratio of thermal and viscous contribution to the entropy production is between one and three when the Reynolds number or hydraulic diameter are optimized. However it is not shown that this is the case when both, Reynolds number and hydraulic diameter, are optimized together.

Lozano and Valero (1993) have developed a theory to allocate entropy generation and monetary cost. In this theory they define a matrix containing all irreversibilities, including irreversibilities associated with the building of installations and the disposal of waste materials. No extensive examples of this theory, including irreversibilities associated with the building of installations and the disposal of waste materials, are available.

Several other researchers have already performed a number of studies on different type of heat exchangers. And studies on the entropy generation minimization design of the heat exchanger system are also documented. Further studies in this field will bring significant improvement in the efficiency of the thermal system.

1.3 Motivation and Objective

The trade-off between the entropy generation during the operation process of a heat exchanger and during the original manufacturing process is the base of the second law method described here. The objective of this thesis is to present an effective and systematic method that uses both the first and second laws of thermodynamics for heat exchanger optimization This method considers the entropy generation during the manufacturing process as an important contribution to the whole entropy generation, in addition to the contribution during the life-time operation process. Here, we should point out that all the entropy generation calculations are based exclusively on the entropy production during the energy conversion procedure. There are other entropy generation sources that need further studies. Using the method described here, heat exchanger and heat exchanger system design will meet life cycle entropy generation minimization criteria.

Chapter 2. Basic Concepts and Methods

2.1 Entropy and economic value

The only reason why thermodynamics initially differentiated between the heat contained in the ocean waters and that inside a ship's furnace is that we can use the latter but not the former. And since the biological life feeds on low entropy, we come across the first important indication of the connection between low entropy and economics. Casual observation suffices now to prove that our whole economic life feeds on low entropy, cloth, lumber, steel, copper, etc., all of which are highly ordered structures. So, we can say that low entropy is a necessary condition for a thing to be useful and in the thermal process the total entropy of the whole system will always increase. The best way to perform a thermal system is to minimize the total entropy generation form it. There is no direct equivalence between low entropy and economic value, there is in each case a conversion factor of the former in to the latter.

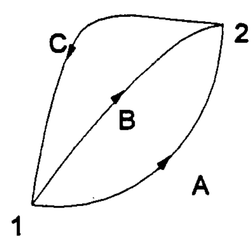
When we use the concept of entropy to analyze the cycles, the accurate definition of the entropy is very important. As will be discussed later, the entropy is a secondary variable or function, calculated from primary variables such as temperature and pressure or volume, it is a step removed from being a dynamic observable variable that describes system behavior. The aspects of its derivation and usage will be very important (Georgescu-Roegen, 1971).

2.2 Derivation of the property entropy and the concept of the entropy change

The discussion of the second law has been primarily conducted in the work of thermodynamic cycles. The property entropy and the entropy generation concept play

prominent roles in these considerations. The property entropy arises as a consequence of the Second Law. Only changes of the entropy are normally of interest. The entropy of any closed system which is thermally isolated from the surroundings either increases or, if the process undergone by the system is reversible, remains constant. So, the change of the entropy can be used as a criterion for reversible operation.

Entropy: Two cycles executed by a closed system are represented in the following figure.



One cycle consists of an internally reversible process A from state 1 to state 2, followed by an internally reversible process C from state 2 to state 1. The other cycle consists of an internally reversible process B from state 1 to state 2, followed by the same process C from state 2 to state 1 as in the first cycle. For these cycles, the convenient Clausius inequality can take the following form. Clausius inequality:

$$\oint \left(\frac{\delta Q}{T} \right)_b = -S_{gen} \tag{1}$$

Two forms:

$$\left(\int \frac{\delta Q}{T} \right)_A + \left(\int \frac{\delta Q}{T} \right)_C = -S_{gen} = 0 \tag{2}$$

$$\left(\int \frac{\delta Q}{T}\right)_b + \left(\int \frac{\delta Q}{T}\right)_C = -S_{gen} = 0 \tag{3}$$

where S_{gen} has been set to zero since the cycles are composed of internally reversible processes. Subtracting these equations leaves:

$$\left(\int \frac{\delta Q}{T}\right)_a = \left(\int \frac{\delta Q}{T}\right)_b \tag{4}$$

This shows that the integral of $\int \delta Q/T$ is the same for both process. Since A and B are arbitrary, it follows that the integral of $\int \delta Q/T$ has the same value for any internally reversible process between the two states. In other words, the value of the integral depends on the end states only. It can be concluded, therefore, that the integral defines the change in some property of the system. Selecting the symbol S to denote this property, its change is given by:

$$S_2 - S_1 = \left(\int \frac{\delta Q}{T}\right)_{\text{int}\,rev} \tag{5}$$

where the subscript ' **int rev** ' is added as a reminder that the integration is carried out for any internally reversible process linking the two states. This property is defined as entropy. Entropy is an extensive property.

Since the entropy is a property, the change in entropy of a system in moving from one

state to another is the same for all processes, both internally reversible and irreversible, between these two states. Thus, Equation (5) allows the determination of the change in entropy; once it has been evaluated, this is the magnitude of the entropy change for all processes of the system between these two states.

As a closed system undergoes an internally reversible process, its entropy can increase, decrease or remain constant. This can be brought out using the definition of entropy change on a differential basis:

$$dS = \left(\int \frac{\delta Q}{T} \right)_{\mathrm{int}\,rev} \tag{6}$$

This equation indicates that when a closed system undergoing an internally reversible process receives energy by heat transfer, it experiences an increase in entropy. Conversely, when energy is removed from the system by heat transfer, the entropy of the system decreases. We can interpret this to mean that an entropy transfer is associated with heat transfer. The direction of the entropy transfer is the same as that of the heat transfer. In an adiabatic internally reversible process of a closed system the entropy would remain constant. A constant-entropy process is called an isentropic process. (Moran, 1995)

2.3 Entropy Generation during operation processes

The major mechanisms responsible for entropy generation in engineering systems are

heat transfer across a finite ΔT, and the flow with friction. In this chapter, we will focus on the general topic of fluid flow and heat transfer, with special emphasis on the thermodynamic aspects of the phenomenon.

2.3.1 Entropy generation due to flow friction

In should be noted that the cost and power requirements associated with the circulation of the single phase fluid are expensive. So, it should be included in any thermeeconomic analysis of heat exchangers.

In the steady flow through a pipe with friction, the entropy generation rate is directly proportional to the mechanical power needed to push the flow through the pipe. The mechanical power is proportional to the end-to-end pressure drop ΔP and the pressure drop is proportional to the wall shear stress acting over the wall-fluid interface. Then, the entropy generation rate and the loss of mechanical power are ultimately attributable to the viscous shearing effect present in the fluid. Estimation of the pressure drop in the heat exchanger is important for design. The pressure drop experienced by a stream that flows through a duct of length L is given by :

$$\nabla P = f \frac{4L}{D_h} \frac{\rho U^2}{2}$$

In this equation, f is called the Fanning friction factor. The literature includes a number of expressions giving the friction factor explicitly. The graphical representation of the friction factor function developed from the experimental data, called a Moody diagram(L.F. Moody

, 1944). To assist computer-aided design and analysis, the friction factor function is available in several mathematical forms, for examples, the Colebrook equationis often cited for turbulent flow inside a pipe:

$$\frac{1}{\sqrt{f}} = -4\log\left(\frac{k_s / D}{3.7} + \frac{1.256}{\sqrt{f}\,\mathrm{Re}_D}\right)$$

Since this expression is implicit in f, iteration is required to obtain the friction factor for a specified Re and Ks/D (R.W. Fox and A. T. McDonald, 1992).

Another expression (Churchill, 1977) that represents the friction factor continuously for laminar through turbulence flow is the following:

$$f = 2\left[\left(\frac{8}{\mathrm{Re}_D}\right)^{12} + \frac{1}{(\alpha+\beta)^{1.5}}\right]^{1/12}$$

where

$$\alpha = \left(2.457\ln\frac{1}{(7/\mathrm{Re}_D)^{0.9} + (0.27k_s/D)}\right)^{16}$$

and

$$\beta = \left(\frac{37530}{\mathrm{Re}_D}\right)^{16}$$

We will use this equation later to compute the pressure drop in a counter-flow heat

exchanger.

A plausible empirical approach for evaluating friction factors of noncircular ducts is to use the hydraulic diameter in place of D in graphical and analytical approaches. The hydraulic diameter is defined by:

$$D_h = 4\left(\frac{cross-section \quad area}{wetted \quad perimeter}\right)$$

Experimental pressure drop data are numerous, but scattered among various sources, including handbooks, manufacturer's data books, and textbooks. These all can be the reference to evaluate the pressure drop effect.

The entropy generation due to the pressure drop can be calculated by the following formula or the integral form of it :

$$\dot{S}_{gen} = \frac{\dot{m}}{\rho T}\left(-\frac{dp}{dx}\right)$$

In some research reports (London and Shah, 1983), The entropy generation associated with the single phase pressure drop experienced by the incompressible fluid moving through the heat exchanger can be modeled. The relationship is given by :

$$\dot{S}_A = \left(\frac{1}{T_{\ln}}\right)\dot{m}_{sp}\left(\frac{\nabla P_{sp}}{\rho}\right)$$

The entropy generation value can be directly compute after knowing the pressure drop value. T_{ln} is the log mean temperature of the single phase flow.

2.3.2 Entropy Generation due to heat transfer across a finite temperature difference

The heat transfer phenomena are always accompanied by entropy generation. There are a lot of different ways to calculate the entropy generation due to heat transfer process. In this thesis, four different methods were used to calculate the entropy generation in the same thermal process.

a. The first method to evaluate the entropy generation is using the general form of the entropy change of an ideal gas. The equation is:

$$S(T_2,P_2) - S(T_1,P_1) = C_p \ln\left(\frac{T_2}{T_1}\right) - R\ln\left(\frac{P_2}{P_1}\right)$$

In the above equation, the specific heat Cp suppose to be constant and this equation is suitable for the compressible ideal gas. If we calculate the entropy change of the incompressible substance, the specific density is constant and the specific heat depends solely on temperature. The change in entropy is:

$$S_2 - S_1 = C\ln\left(\frac{T_2}{T_1}\right)$$

When we find the operation condition of the heat exchanger, we can use the above

equation, and calculate the entropy change during the thermal process.

b. The second method to evaluate the entropy generation is useful when considering any internally reversible process linking the two states. The entropy is an extensive property. Since the entropy is a property, the change of the entropy of a system between two states is the **same** for all processes, both internally reversible and irreversible. So we can use the following erquation as:

$$dS = \left(\int_1^2 \frac{\delta Q}{T} \right)_{\text{int}\, rev}$$

to evaluate the entropy change in the heat transfer process. In a control volume, the heat input at a higher temperature, which can be called heating load, and the energy transfer out of the system at lower temperature, which can be called cooling load, will determine the value of the entropy generation in this control volume. Here it is very important to clarify the confusing concept of exergy which depends on an unclear definition of the environmental temperature. The temperature used in this thesis is the entropic average temperature of the higher region and the lower region, respectively. So the entropy generation in this case is :

$$S_{gen} = \frac{Q_L}{T_L} - \frac{Q_h}{T_h}$$

The entropy generation calculated in this way is the sum over all entropy generation processes constituting the cycle. For the further discussion on this issue, a number of

references are available, for example (K. Amrane and R. Radermacher, 1994).

c. The third method is using software to directly find the entropy value at each specific point. If we can identify the necessary thermal condition of that specific point, such as temperature and pressure. The EES (Engineering Equation Solver) software can help to find the entropy at that specific point and the enthalpy at that point too. So the entropy change is determined and the heat transfer or the work transfer across the boundary of the control volume can be found. It is easy to evaluate the entropy generation ratio in this way. This shows the advantage of using the EES software. It can be programmed to simulating the thermal cycle, by changing the specific parameters, the optimization process can be realized directly.

d. The last method can be used to verify the correctness of the former three methods. Bejan gives a formula (Bejan 1996) to calculate the entropy generation in internal flow :

$$S_{gen} = \frac{(q')^2 D_h}{4T^2 \dot{m} c_p St}$$

The specific parameters in this equation are defined as follows. St is the Stanton number and f is the friction coefficient between the fluid and the wall of the tube. This equation takes the temperature and the pressure drop terms into account.

After careful comparison, these methods yield the same results. In the calculation in the next chapter, the simplest method was used to calculate the entropy generation due to heat transfer. In different cases, different methods can be used. Some of them will introduce

dimensionless numbers to reflect the influence of the temperature difference and the pressure drop (Bejan, 1996). This calculation process is more complex and the information needed to realize the calculation is sometimes difficult to find. So in this effort, we only use the first three methods listed above. In the next chapter, an example will be used to compare these methods.

2.4 Entropy Generation during manufacturing processes

2.4.1 Energy consumption during production of materials

The production of metals and their conversion to a saleable form is of fundamental importance to all industry-based economies. For example, the metals industries use about 20% of the total energy consumed in the whole industry. The evaluation of the energy required (or entropy generated) by systems that produce metals and metal products is an important part of energy analysis and of the entropy generation analysis.

At the same time, we should notice that the information concerning the energy input to produce some form of materials always depends on the detail of the manufacturing process. Different companies operating apparently identical systems frequently consume different amounts of energy, indeed this effect frequently occurs in different factories within the same company. Such variations arise from the different ages of plants, different levels of maintenance and different practices. Before using the data, the system and the manufacturing should be described. The published data is scattered throughout the literature. In this thesis, searching and comparing the related data is an important part to establish the model of life-cycle analysis. Here are some useful research result that can be used in the entropy analysis

procedure.

A detailed energy analysis of the primary anode copper process is presented by Kolenda et al. (1992). The cumulative irreversibility of the flash smelting process, one of the main copper production processes, is shown to be 45.8 MJ per kg anode copper. Including the energy consumption due to discharge and dissipation of materials into the environment, like slag and combustion gasses, gives a total cumulative energy consumption is of 55.6 MJ per kg primary anode copper.

The cumulative energy use of the production of solid copper out of anode copper is around 4.5 MJ/kg copper according to Boustead and Hancock (1979). The entropy increase is almost zero and we assume the enthalpy values of the inputs to represent the change in energy values, so this value is taken for the expended energy. The cumulative energy consumption for primary copper becomes 55.6 + 4.5 = 60.1 MJ/kg. Boustead and Hancock (1979) give two totally different values for the energy consumption of the secondary copper production, namely 7.2 and 48.8 MJ/kg. This difference just illustrates the importance of checking the source and application of the data.

The energy use for the production of primary steel slabs is 10.5 MJ/kg according to Worrell (1992). The cumulative energy use of secondary steel is calculated from Wall (1986) by assuming the efficiency of the electricity production to be 0.95. The energy use associated with the production of the alloying materials and lime has been neglected.

The manufacturing process of the steel tubes includes hot and cold rolling and the bending of the tube. The energy consumption of hot and cold rolling is 5.3 MJ/kg according to Worell (1992). The energy consumption of the bending of steel has been estimated by

assuming that metal is heated to 900°C by a gas heater. The energy consumption associated with the force required to bent the steel has been neglected. The energy consumption associated with welding of steel tubes has been estimated to be 0.260 MJ per meter, according to the Dutch steel maker, Hoogovens IJmuiden. The energy consumption associated with the manufacturing of the copper tubes, which includes the welding of copper tubes, is 14.7 MJ/kg according to Alvarado-Grandi (1989).

The heat exchanger outer shell is always insulated by polyurethane (PUR) foam with a thickness of 0.025 m. The cumulative energy consumption for the production of PUR with a density of 30 kg/m^3 is 71MJ/kg according to Kindler et al. (1980). No recycling of the PUR has been assumed.

The energy consumption associated with the manufacture of the heat exchangers is due to the production of copper tubes and steel tubes, welding and the production of the PUR-foam. The detailed information about the energy consumption in different metal production processes are listed in the related reference or handbook and should be used carefully due to the different definition and forms of the energy that is consumed. After getting the information about the energy consumption to produce the different materials, we can calculate the total energy input to manufacture the heat exchanger. To obtain the consistency of the result, the energy consumption data of the Copper, Steel and Aluminum will be used from the same reference book (W.E.Franklin, D. Bendersky , 1975). The book gives the average energy consumption to produce the primary and secondary form of those metals. The primary form refers to the product that is manufactured from the raw materials (ores) and the secondary form refers to the product that is recycled. The energy required to

recover and recycle ferrous metals, aluminum, and copper from the wastes is considerably less than the energy requirement to produce these metals from ores. In the industrial applications, certain amount of those metals are produced from the secondary form.

From the research results, remarkable agreement exists on the total energy requirement for steel manufacture from ore. The average value is 49×10^6 Btu/ton (1kwhr=1.05×10^6 Btu). The total energy requirement of steel produced from scrap was evaluated as 6.75×10^6 Btu/ton, which is only 14 percent of the energy requirement to produce steel from ore. The recycle ratio of the steel is about 0.16. That means 16 percent of the total steel product is produced from scrap. The average energy consumption to produce the steel can be calculated from the above data.

The U.S. copper industry is composed of integrated primary producers (from ore to fabricated product, copper wire and brass fabrication), and the secondary copper industry. Study shows that 45 percent of total U.S. copper consumption is constituted by recycled copper scrap. From the research result (W.E. Franklin, D. Bendersky , 1975), 6.7×10^6 btu/ton represents the best estimate of the true energy requirements for producing copper from scrap, while the energy input to produce the copper from ore is 71×10^6 btu/ton. Based on the above information, the average value of the energy consumption to produce the copper can be determined also.

In aluminum production industry, the energy consumption to use the ore to create the aluminum is estimated as 251×10^6 Btu/ton , while the energy input to use scrap to create the aluminum is 9.5×10^6 Btu/ton. And the recycling ration in this case is 0.23. (I. Boustead and G. F. hancock 1979).

The above data will be used as the base to perform the calculation of the entropy generation during the manufacturing process.

2.4.2 Entropy generation in production of materials

The information listed above will be used to calculate the total energy input in the manufacturing process of a counter-flow heat exchanger as an example. From there, the entropy generation associated with the material will be determined based on the energy consumed, its form and related conversion process, and included into the total entropy generation of the system. The principle to calculate the entropy generation during the manufacturing is described below:

a. Identify the main process of producing the metal or non-metal materials to make to the heat exchanger and find out the energy input value in each step.

b. Identify the operation condition such as temperature, pressure at each step.

c. Evaluate the entropy production ratio (the entropy generation value over the energy input value) of each step. This ratio value can be evaluated in an independent typical cycle, such as Rankine cycle, Otto cycle, the combustion process or electricity generation process.

d. Use the information from above, evaluate the total entropy generation during the whole material production process. Find the value of the entropy generation on every mass unit of the material.

No published report evaluated the entropy generation associated with materials production to make a heat exchanger. In this thesis, these values are evaluated. They will be used to identify the entropy generation contribution from the materials used in a heat exchanger or heat exchanger system. Then, they will be contributed to the calculation of total

entropy generation during the whole life-cycle and will be treated as a portion of the optimization model.

2.5 Other economic input that is not accounted for

There are other contributions related to the entropy generation during the manufacturing process. This thesis calculates the entropy generation based solely on the energy conversion process. The energy input to those contributions are not included in this thesis. In further study, these factors should be calculated as the capital investment of the energy, because we can also treat every economic process as an entropy increase process. These parts are normally treated as economical expenses of the system.

The additional sources of the entropy generation are listed below:

2.5.1. Supervisory and clerical labor: The energy input of this part is based on the operating labor cost. The value of this part depends on the complexity of the process.

2.5.2 Utility cost: This part contains several separately escalating components, such as electricity, process steam, refrigerants, compressed air, cooling water, heated water, hot oil or process water, and so on. Utility costs generally compose two main categories. One is the material and labor, these cost can be evaluated by some standard index, such as CE (Chemical Engineering) plant cost index. The other is the energy consumed during the operation period of the system. These values also can change in several ways.

2.5.3 Maintenance and repair: This part constitutes an important and necessary part in any operation. The factor of this category is in the range of 2 to 10 percent of the total investment. The low limit is reached when the system is well-designed and rather simple. On the other hand, the higher limit should be used, when the system is unconventional in design

or complexity. Generally, 6 percent is recommended.

2.5.4 The other contributions that should be considered are: design effect and supplies, lab test effects and disposal of waste material.

2.5.5 Another contribution to entropy production results from the fact that when material is processed, its crystalline structure, purity and other parameters may change that also effect the entropy production..

Overall, these contributions of the cost and thermodynamic studies should be evaluated at this stage and then the corresponding entropy generation rate determined. However, at this stage of the effort, they were considered to be negligible in order to limit the scope.

2.6 Discussion of the human labor and entropy generation

Almost all industrial processes involve the use of the manpower which consume the energy in the form of the food. So it is also important to evaluate the energy input to the human body and the entropy generation from this process. If the human digestive process is treated as a combustion process, the entropy generation from this process can be calculated by analyzing the entropy value difference between the initial material and the final products. This just approximately evaluate the entropy generation during the digest process. Further study on this issue should be performed to find a more precise way to describe the entropy generation during this complex process.

On the other hand, the amount of the energy consumed by human labor is relatively small compared with the total amount of energy contributed to the manufacturing process. The average energy extracted from food per day by a human is of the order of 0.144 MJ per

kilogram of body weight (Anon 1975). For an adult of mass 70 kg, this corresponds to a daily intake of about 10MJ. The greater part of this consumption is required to maintain the man as a living organism rather than as an industrial component. A contribution of the order of 5 MJ/day may be attributed to the industrial work actually performed. If we compare this with the consumption of a machine operated by the man, we will find a big difference in the term of the energy consumption. In a day, a normal injection mounding machine consumes 8220 MJ. The man's energy contribution is only 0.06% of the machine energy requirement. In fact, in most operations in highly industrialized systems, the contribution from human labor is less than 0.5% and can safely be neglected (I. Boustead and G.F. Hancock, 1975). So the inaccuracy of the evaluation of the entropy generation ratio from the human labor will not influence the result of the total system optimization design.

2.7 The method of the thermoeconomic cost evaluation

Thermoeconomics is the branch of engineering that combines entropy analysis and economic principles to provide the system designer or operator with information not available through conventional energy analysis and economic evaluations but crucial to the design and operation of a cost-effective system. Thus, the thermoeconomics can be treated as entropy-aided cost minimization. After performing the traditional thermal analysis of the system, the entropy generation can be evaluated. More often, we need to know how much such inefficiencies cost. Knowledge of these costs is useful for improving the cost effectiveness of the system, that is, for reducing the costs of the final products produced by the system. In chemical plants, the electrical power, chilled water, compressed air, and steam at various

pressure levels are generated in one part and transferred to another part. The true cost at which each of the utilities is generated should be evaluated. These costs are then charged to the appropriate final products according to the type and amount of each utility used to generate a final product. In the design of a thermal system, such cost allocation assists in pinpointing cost-ineffective processes and operations and in identifying technical options that might improve the cost effectiveness of the system. (G. Tsatsaronis, 1984)

So, the objective of a thermoeconomic analysis might be:

a. To calculate separately the entropy generation of each product generated by a system

b. To understand the entropy generation process and the flow of the cost in the system

c. To optimize specific variables in a single component

d. To optimize the overall system

In this thesis, the above procedures will all be performed during the whole process of the thermal optimization analysis. In the conventional thermo-economic analysis, the capital cost is chosen to be the criterion to be minimized. In this thesis, the energy content of each step is determined. Entropy generation is used as the criterion to evaluate the effectiveness of the system in its life cycle.

Advanced power plants and energy intensive chemical processes can be analyzed and optimized using the thermo-economic method. Here are some energy conversion systems that can be analyzed and improved in further study:

1. Conventional steam power plants
2. Integrated gasification combined-cycle power plants
3. Other advanced coal fired concepts

4. Advanced gas turbine systems

5. Heat exchanger networks

6. Crude oil distillation unit

In general, the entropy generation minimization method will more and more show its advantages in its further application in a various kinds of industries.

2.8 Method of optimization

Optimization, or the urge for efficiency, has a basic psychological origin. We can confront a task or problem and recognize more than one course of action, followed by a second phase, the selection of what is considered the best action. The second phase is the decision step. The two steps taken together, recognition of the objectives and decision, constitute optimization (Jelen, 1970). Optimization can be judged by human preference or detected by exact mathematical means. As engineering becomes more and more advanced and the business and industrial world more competitive, the methods for optimization become more exact and the rewards increasingly greater.

A number of methods have been introduced to determine optimum procedure. The three fundamental and powerful general methods are analytical, graphical or tabular, and incremental. In this study, most studies use graphical and tabular method. This is based on the nature of this kind of problem. EES has a build-in function to find the optimum, which will be used in this study.

Chapter 3. The Second-law Entropy Generation Analysis

3.1 Basic principles of the entropy generation

The thermodynamic science was developed with the primary objective to understand the relationships between chemical, thermal and mechanical phenomena. Modern industry has to apply that understanding into the engineering process analysis. So, when attempting to describe the total energy assumed or the total entropy generated when a product is manufactured, we should not only consider the energy consumption in the last manufacturing step. As any thermal design, the entropy generation analysis should follow some basic procedures. Here, the main steps of this method are discussed.

The objective of the design is to minimize the total entropy generation from the entire system or from any component in the system that will still satisfy the original thermal and design requirements. To realize this objective, a model of the total entropy generation should be established. All the entropy generation calculations are based exclusively on the entropy production during energy conversion.

In this analysis, the total entropy generation includes two main contributions. One is the entropy generation during the operation of the device within its lifetime. The sources of the entropy generation from this category are the entropy generation from the heat transfer process and the entropy generation from the fluid flow process. There are several ways to evaluate the value of it and the detailed evaluation procedures have been discussed in a former part of this thesis.

The second contribution of the entropy generation results from energy conversion during

the manufacturing process. As we can understand, even the same amount of the same material, if they are produced in different ways, the energy consumption and the corresponding entropy generation are different too. Even when we consume the same amount of the energy, the entropy generation values in different industrial processes, such as combustion process, power generation, etc., are different. In the entropy generation analysis, to equalize the difference of this, the energy-entropy conversion factors , or called as entropy generation ratio in different industry processes should be evaluated. This work will be performed in this chapter. As we mentioned before, another contribution to the entropy generation from the manufacturing process is human labor. The entropy generation from this contribution should be treated as another source of total entropy generation. In the last chapter, evaluating the reasonable energy-entropy conversion factor for the human labor contribution was also completed, and the usage of this human-labor entropy energy conversion factor will not influence the final result too much, as we discussed in the former chapter.

After discussing each contribution, the mathematical model of the total entropy generation will be developed. The total entropy generation during the life-cycle, including the operating process as well as the manufacturing process will be a function of several physical parameters of the heat exchanger, such as the size of the heat exchanger, the number of the heat exchange tubes, the material of the heat exchanger. It will also be a function of the operating conditions of the system, such as the inlet and outlet temperature of the fluids in a given heat exchanger, the load requirement of each component, the pressure drop across the heat exchanger, and so on. The total operation period of the heat exchanger is also

considered as a factor that influences the total value of the entropy generation. During this preliminary study, a limited number of the parameters are treated as variables, while the change of the total entropy generation due to the change of those parameters are observed.

The mathematical model of the total entropy generation will then be used for the optimization process. In this thesis, after establishing the model, EES software was applied. The total entropy generation value is the objective function. Then the thermal design of the component or system can be accomplished by minimizing the total entropy generation. The detailed analysis of the different parameters' effect on the objective function, which is entropy generation value will be shown by different graphs in the next chapter.

Generally, the main procedures of the entropy analysis are listed as follow:

1) Define the total system (A heat exchanger in this thesis).

2) Analyze the sources of the entropy generation for the whole system

3) Calculate the energy-entropy conversion factors for different processes

4) Find the expression of the entropy generation for each source

5) Describe total entropy generation as a function of various physical parameters

6) Conduct the optimization of the design by minimizing entropy production

7) Find the best working condition of the heat exchanger related to the physical parameters of the heat exchanger

3.2 Energy analysis of the thermal system

When analyzing a thermal system, the system boundaries are defined at the beginning. Then all energy and material flow in this boundary are identified. So, the objective function

of the optimization is established as discussed next. In this chapter, the entropy generation ratio of different cycles or thermal processes are the main concern. To obtain this value, the first and the second law of thermodynamics should be applied together with the help of system energy analysis.

3.2.1 Input and output analysis

The following diagram shows energy and material flows in an industrial process. In the horizontal direction, the material flows are shown, while in the vertical direction, the main energy flows are shown. In both directions, the energy and the material flows should obey the first law of thermodynamic.

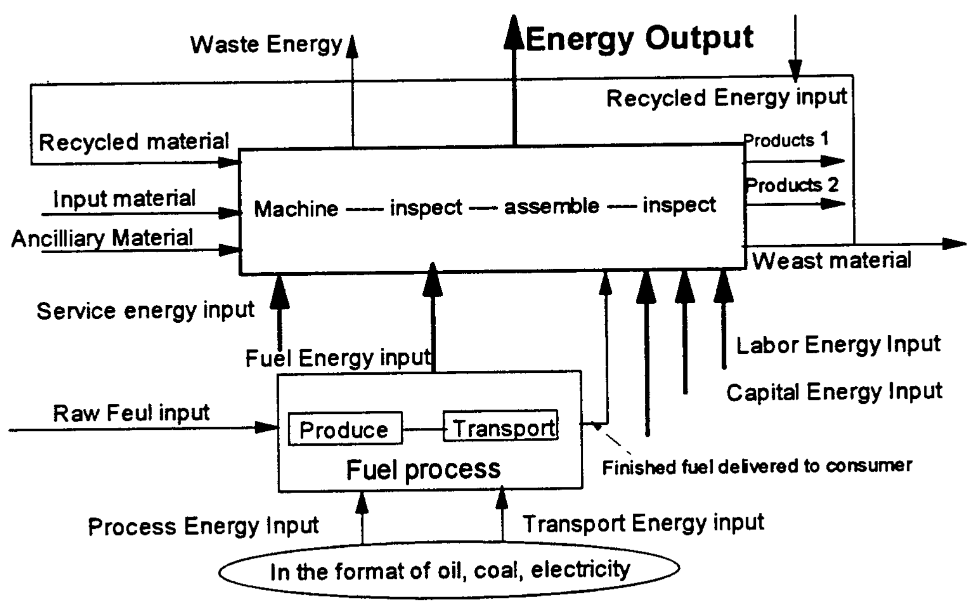


Figure 1. Schematic of the materials and energy flows in an industrial operation system

When the system is analyzed with the entropy generation minimization method, each

input term is calculated by a specific method to find the corresponding entropy generation for this term. This is the application of the second law. Then the total entropy generation for the system is determined as a function of different parameters, such as temperature, pressure, chemical properties, the efficiency of each component, and so on.

3.2.2 Discussion of the major terms in the diagram:

Following terms are important in the diagram above:

1) The capital energy: This term refers to the energy used in the process of constructing the component or the system.

2) The operation and the maintenance energy: To keep the thermal system working in the given condition, the energy input for operation and maintenance needs to be calculated. In most cases, this contribution is very important in the life-cycle analysis. The magnitude of this contribution depends on the trade-off between the design complexity of the system and the capital investment.

3) The material production energy input: On the whole, the energy input to produce the different kinds of metals from their primary form will use up to 20% of the total energy input of the whole industry. Some research has been conducted to evaluate the energy input to manufacturing different kinds of metals in various forms. When applying the related value of energy consumption, we should pay attention to distinguish that when the product was made by a different method, the energy computation and result thereof is also different.

4) The fuel energy input: This part may be divided into two parts: the energy input to produce the fuel and the energy input to transfer the fuel. Generally, the form of fuel in this

case may also include electricity as well as oil, gas and others.

5) This diagram just shows the sources of a closed thermal system. In other studies, analyses may show different diagrams of energy and material flows.

3.3 Using the EES software

As thermal system design involves considerable analysis and computation, use of computers can facilitate and shorten the design process. Benefits of computer-aided thermal system design are expected to include increased engineering productivity, reduced design costs and result exhibiting greater accuracy and internal consistency.

Computer-aided design relies heavily on suitable equipment and design programs. EES(Engineering Equation Solution) is a very powerful software tool for thermal design. It has many advantages that which is suitable to apply in the entropy analysis.

In the traditional thermal analysis, there are different materials, such as oil, water, different kind of gases, or their corresponding liquid or solid form. and different kind of refrigerants, these materials' physical properties are always found in the some tables or graphs in some reference book. Sometimes, these data lack the consistency with each other in different reference book. The English and SI unit conversion may also cost some additional time.

The first advantage of the EES software is that it contains a property database for all materials of interest. It also realizes unit conversion from the English unit to SI unit, or vice verse.

The EES software can also create graphs to show the relationship between the related

data as well as displaying it in table format. This will greatly help the user to analyze and demonstrate the relationship between variables.

The other feature of the EES software, which is extremely suitable for this study, is that it can perform the optimization process. We can realize the entropy generation value minimization by using a specific function in this software. There are several ways to realize the optimization in the EES software. To use those ways effectively and correctly, the user should understand the mechanism of each optimization method. Otherwise, it is possible to find a value which is actually not the optimization value needed. The detailed discussion of the different ways of optimization can be found in the last chapter. EES manual or other related mathematical references are also informational.

In this thesis, EES program was written to simulate different kinds of the thermal processes. The entropy generation ratios as defined before in these processes are calculated. In this chapter, different cycles, such as Rakine cycle and Otto cycle, are evaluated. In the next chapter, the optimization will be performed on the life-cycle level to design a heat exchanger.

3.4 Introduction Example: Cross-flow Heat Exchanger

As a simple example, the entropy generation rate from a cross-flow heat exchanger will be calculated using different methods. The results of different methods were compared. The thermal and physical parameters of this cross-flow heat exchanger come from the classic heat exchanger design book (London and Kays, 1947).

TABLE 1. Results from different ways to compute S_{gen}

	method a	method b	method c	method d
S_{gen} (Unit:W/K)	7468	6067	6552	7135

The result shows that these methods are comparable in terms of the entropy generation value within ±10%. But they are more or less complicated to use and need more or less information than others. So, in the later calculation, the easier or often the only way will be chosen to compute the entropy generation value.

3.4 Entropy Generation in a Combustion Process

Combustion is an oxidation process and is usually exothermic (release the chemical energy contained in fuel as thermal energy). When a chemical reaction occurs, the bonds within the molecule of the reactants are broken, and atoms and electrons rearranged to form new products. In combustion reactions, rapid oxidation of combustible elements of the fuel results in energy release as combustion products are formed. The three major combustible chemical elements in most common fuels are carbon, hydrogen, and sulfur. Sulfur is usually a relatively unimportant contributor to the energy release. A fuel is said to have burned completely if all of the carbon present in the fuel is burned to carbon dioxide, all of the hydrogen is burned to water, and all of the sulfur is burned to sulfur dioxide. (D. E. Winterbone, 1997)

In many of our energy conversion processes, as in conventional power plants, we rely on chemical energy being released in a combustion process. The combustion of fossil fuels, usually employed as an intermediate step, is in common practice highly irreversible. This is the

main reason for the overall low efficiency of these energy conversion processes. So, the entropy generation from the combustion process is an important portion to be analyzed.

The human body, as an example, produces mechanical energy from chemical energy by allowing many intermediate chemical reactions of the 'fuel' and the 'oxygen' separately before one molecule of 'fuel' is united with the stoichiometric number of oxygen molecules in the muscle cells, where the mechanical energy is produced. Though the total amount of the energy consumed in this process is not as huge as the energy consumed by machine or industry combustion chamber, and the intermediate processes are far more complex than the normal combustion process we encounter, this process can be simplified as another combustion process in the present study. The entropy generation from this process so can be evaluated in a similar way like combustion process which we will explain in detail in next section. So the human labor factor can be counted into the final entropy generation analysis (H. J. Richter and K. F. Knoche, 1983).

3.4.1 Calculation of Entropy Generation from a basic combustion process

The procedure of calculation of the entropy generation from the combustion process is:

1) Establish the chemical reaction equation of the main process

2) Evaluate the entropy value of each reactor and product by using EES.

3) Calculate the net entropy increase by subtracting the total entropy of the reactor from the total entropy of the product

4) Normalize the entropy generation rate to the total heat generated from the combustion process.

A common combustion process is used to demonstrate the procedure listed above. From this calculation, the entropy generation rate corresponding to the total heat generation is determined and will be used in the following the comprehensive of a life-cycle thermal system analysis.

In this case, the entropy generation from one specific chemical reaction was calculated. The chemical equation for the complete combustion of methane with oxygen is

$$CH_4 + 2\ O_2 \Longrightarrow CO_2 + 2\ H_2O$$

The change of the entropy in this reaction is $S=S_p-S_r$, where S_p and S_r are entropy of the products and entropy of the reactants, respectively. The operation condition of this combustion process is:

1) The higher temperature is 900K, the lower temperature is 298K
2) The higher pressure is 3 bar, the lower pressure is 1 bar
3) The reactants in this case are CH_4 and oxygen, the products are CO_2 and water

At given conditions, the entropy value of each term can be obtained from EES. Then the entropy change from this process is calculated as :

$$S_{gen}=S_p-S_r$$

At the same time, EES software can give the value of enthalpy of every material to eval uate the heat generation from this reaction. So, the ratio of the entropy generation from this reaction to the total amount of the heat created can be determined.

After calculation, the entropy generation ratio during the combustion process above is: The entropy generation from this process is 66.21 kJ/kmol-K, the heat generation from the reaction is 328082 kJ/kmol, so the ratio as defined before is **0.22 kJ/K/MJ.**

3.4.2 Calculation of the entropy generation for human body

The entropy generation rate from human body need to be evaluated because human labor contribution may be important in life-cycle entropy analysis. Here, the human body may be treated as a combustion chamber. It consumes the foods that reacts with the oxygen. The procedure to evaluate the entropy generation here is similar with that of the basic combustion process. The entropy generation rate corresponding to total heat generation then can be determined. The only difference in this case is that the chemical reaction in the human body is evaluated as:

$$2\ C_2H_6 + 7\ O_2 \Longrightarrow 4\ CO_2 + 6\ H_2O$$

And the temperature of this reaction is assumed to heat normal human body temperature. The entropy generation corresponding to total heat generation then can be determined.

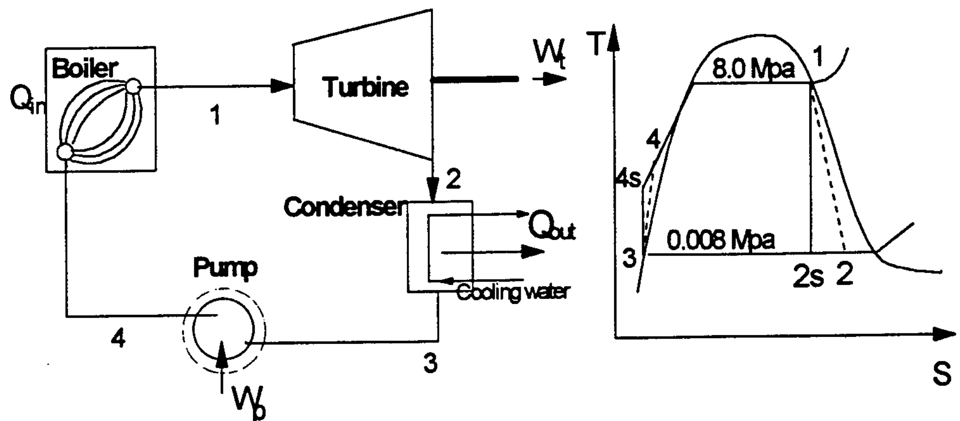
The entropy generation ratio of the human body is: **1.08kJ/K/MJ.**

3.5 Entropy Generation in a Rankine Cycle (Steam Turbine Plant)

Next, the entropy generation from a thermal cycle was evaluated. The Rankine cycle is composed of boiler, turbine, condenser and pump. The given working condition for a Rankine are listed below:

1. Saturated vapor enters the turbine at 8.0 MPa.
2. Saturated liquid exits the condenser at a pressure of 0.008 MPa
3. The cooling water enters the condenser at 15 C and exits at 35 C.
4. The net power output of the cycle is 100 MW

5. The working fluid is steam.



Schematic of Rakine cycle and given condition

Figure 2

The assumptions are listed next:

1. Each component of the cycle is analyzed using a control volume at steady state.

2. The working fluid passes through the boiler and condenser at constant pressure. Saturated vapor enters the turbine. The condensate is saturated at the condenser exit.

3. The turbine and pump each operate adiabatically with an efficiency of 85%.

4. Kinetic and potential energy effects are negligible.

After calculation, the entropy generation ratio of the Rankine cycle in this condition is:

1.715 kJ/K/MJ.

3.6 Entropy Generation in an Otto Cycle (Gas Turbine Plant)

The Otto cycle is an ideal cycle that assumes the heat addition occurs instantaneously while the piston is at the top dead center. This kind of cycle is widely used in the automotive

industry. It is necessary to analysis the entropy generation in this process. The Otto cycle consists of four internally reversible processes in series. Two of them are isentropic processes in which there is no heat transfer but only work, the other two are constant volume processes, in which there is heat transfer but no work. The heat transfer and the work performed can be evaluated as well as the entropy generation from the whole system by using EES. Then the ratio of the entropy generation to the total heat generated or to the work performing by this cycle can be determined for the later usage.

After calculation, the corresponding entropy generation rate of the Otto cycle is :

0.8526 kJ/K/MJ

3.7 Entropy Generation in the electricity production process

The electricity production process is transfer the mechanical energy to the electric energy. From the literature, the conversion factor of transferring the mechanical energy to electric energy is 95%. So, We can calibrate the entropy generation rate from this category. After calculation, the entropy generation ratio during electricity generation process is:

3.218 kJ/K/MJ.

During the metal production process, we assumed that most of the energy consumption is in the form of electricity. The entropy generation ratio of other steps in the metal production process also uses the same ratio as the ratio of electricity generation. If the energy input is given, the entropy generation will be determined.

Chapter 4 The Life-Cycle Entropy Generation Analysis

4.1 Life-cycle entropy generation calculation procedure

Different processes were discussed in the above chapter and the entropy generation ratio of them were determined. Here we choose a counter-flow, water-to-water heat exchanger to perform the life-cycle entropy analysis. The critical point of this analysis is to combine the entropy generation during the operation process and the entropy generation from the manufacturing process. In most of the thermal design so far, the focus is mainly on the optimization of the thermal process. In industrial applications, a successful thermal design should also consider the energy consumption during manufacturing process and other sources of the energy consumption. The connection between the operation process and manufacturing process is the concept of the entropy generation during these processes. It turns out that both of them will influence the total entropy generation to a certain degree. When considering the life cycle operation, neither of them should be neglected. The entropy generation value also objectively reflects the irreversibility of the energy conversion process.

The computation and the analysis using this method is applied to a simple counter-flow heat exchanger, and the entropy generation value is only based on energy conversion processes. As we mentioned in the former chapter, there still are some other factors will influence the total entropy generation as shown in a previous chapter. In this study, the entropy generation during the manufacturing process is evaluated in the following way:

1. Compute the entropy generation ratio of different processes, such as combustion process, power generation process, all these processes should be involved into the material

production processes (See above).

2. Determine the energy content value of different materials. This has already been discussed in a former chapter.

3. Calculate the entropy generation value during the manufacturing process of a certain amount of material being used to build the heat exchanger. The main point of this chapter is to show the result of the analysis in this specific heat exchanger. This step is based on the first two steps.

To perform the entropy generation life-cycle analysis, several groups of the conditions are set during this study.

a. The physical parameters of the heat exchanger are defined. This group of values include the length and the diameter of the heat exchange tube and shell, and so on. The length of the heat exchanger is set to 4 meter as the base case. The length of the heat exchanger will be changed and optimized in later case. It shows that this value can be optimized. In a similar manner, the diameter of the inside tubes and outside shell all can be optimized. Also, due to the design requirement, the thickness of the tubes and shell should be consider as one parameter to be evaluated and optimized. However, the strength of the materials should be considered to satisfy the physical requirement.

b. The operation conditions of the heat exchanger are given, such as the temperature and the pressure. While the mass flow rates of this heat exchanger on both side are the same and kept constant at 0.5 kg/s, the inlet temperature of the flow to be cooled is 65°C , the outlet of it is 10°C. The inlet pressure is supposed to be 1 atmosphere pressure. The outlet pressure can be determined after calculating the pressure drop by using given correlations.

c. The materials are chosen, in this study, the materials are steel, copper and aluminum.

d. The working fluids on both sides are given, for the sake of simplicity, water is chosen to be the fluids on both side. The physical properties are assumed to be constant. The correlations which apply to incompressible flow can be used here to calculate the friction factor and heat transfer coefficient.

e. The total amount of the heat transfer is kept constant as 10.45 kW.

f. The length of the operation period should be given. In this study, the heat exchanger life time is set to 5 years. The heat exchanger is supposed to be used 24 hours a day, 365 days a year. Thus, the total number of hours in its life time is determined.

The main sources of the entropy generation are:

a. The entropy generation from the manufacturing process.

b. The entropy generation from the heat transfer and fluid flow.

c. The entropy generation when assembling parts.

d. The entropy generation from the utilities.

The entropy generation ratios were evaluated for each category by using the different methods discussed above. So, the total entropy generation ratio is a function of the length of the heat exchange tube, the diameter and the number of the heat exchanger tubes, the temperature difference between the two fluids and the pressure drop across the total tube length. These factors are related to each other. The EES software was used to perform the optimization of the design.

The first step of this analysis is to establish the model of the total entropy generation. The final mathematical model is established in this study, which accounts for all parameters

listed above. By changing different parameters, the trend of the entropy change influenced by these modifications can be identified.

4.2 Results and Discussion

In industrial applications, the choice of which material is going to be used is an important issue. In this study, three different kinds of the metals, copper, steel and aluminum, are chosen to be compared with each other. Especially, the difference between copper and aluminum is interesting to discuss. The criterion of the discussion is the entropy generation from the heat exchanger during the entire life-cycle process. Under this condition, the other parameters of the heat exchanger are kept the same.

First, the shell of the heat exchanger is made of steel. The length, the thickness and the diameter of the shell will be kept constant. The working condition, such as the inlet and outlet temperature and pressure will be kept constant too. The assumed life-cycle operation period for both of the heat exchangers is also kept constant. The number of the tubes inside the heat exchanger is the same for the convenience of comparison. The only difference between the two heat exchangers is the material of the inside tubes. One set is made of copper, the other set is made of aluminum. Then the calculations are performed. The results are listed in the following tables (table 2 and table 3).

From the calculation, the entropy generation from the two materials at the same volume are similar (see table 2 and table 3). In those tables, the first column lists the number of the tubes inside the shell. In the second and the third column, the entropy generation from the thermal operation process and the entropy generation from the manufacturing process are

listed, respectively. The last column is the total entropy generation from this heat exchanger during its whole life-time. It is the sum of the second and the third columns. Minimum entropy production causes a higher entropy generation than copper per unit volume. The total minimum entropy generation from the aluminum heat exchanger is 13% higher than the entropy generation from the copper heat exchanger. For copper, the minimum entropy generation is found at 35 tubes, for aluminum at 27 tubes. But the weight of aluminum will be far less than that of copper. So, if we use the aluminum under the same conditions, the weight of the heat exchanger will decrease. In some applications, this is a big advantage. The weight penalty will be accounted for, when this study is extended to include entire systems.

The result of other conditions are listed below. From figure 5 to figure10, result for different cases are shown and discussed thereafter.

TABLE 2

The entropy generation value during the operation period in a copper heat exchanger

Unit: S: [kJ/K]

N	$S_{thermal}$	S_{manu}	S_{total}
10	20795	8122	28917
15	13882	9131	23013
20	10418	10141	20599
25	8338	11151	19489
30	6950	12160	19110
35	5959	13170	19128
40	5214	14179	19394
45	4636	15189	19824
50	4172	16198	20371
55	3793	17208	21001

TABLE 3

Entropy generation value during the operation period in an aluminum heat exchanger

Unit: S: [kJ/K]

N	$S_{theraml}$	S_{manu}	S_{total}
10	20795	8949	29744
15	13882	10372	24254
20	10418	11795	22213
25	8338	13218	21556
30	6950	14641	21591
35	5959	16064	22023
40	5214	17487	22702
45	4636	18910	23546
50	4172	20333	24506
55	3793	21756	25550

Figure 3. Life-cycle entropy generation of an aluminum heat exchager

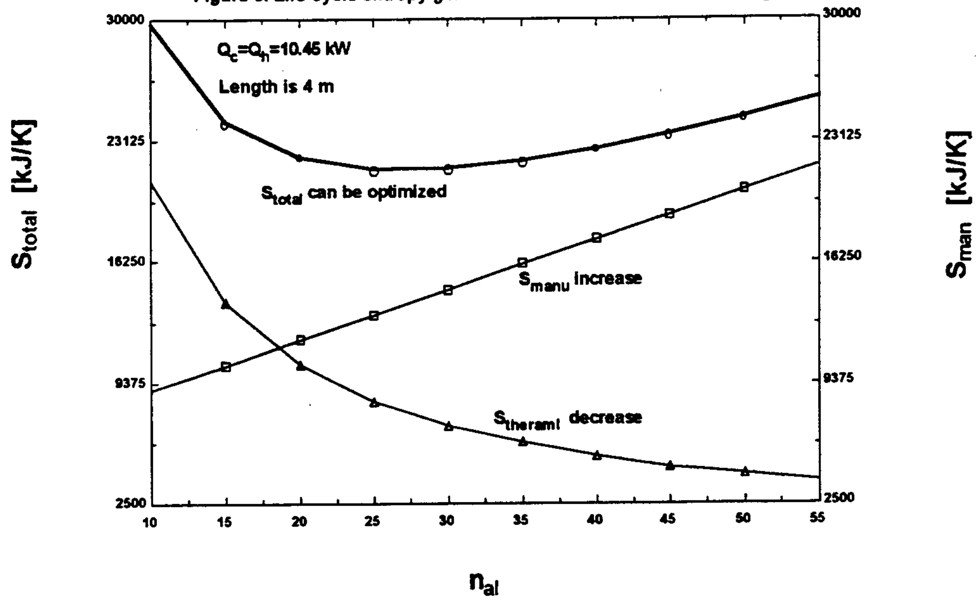


Figure 4. Life-cycle entropy generation of a copper heat exchanger

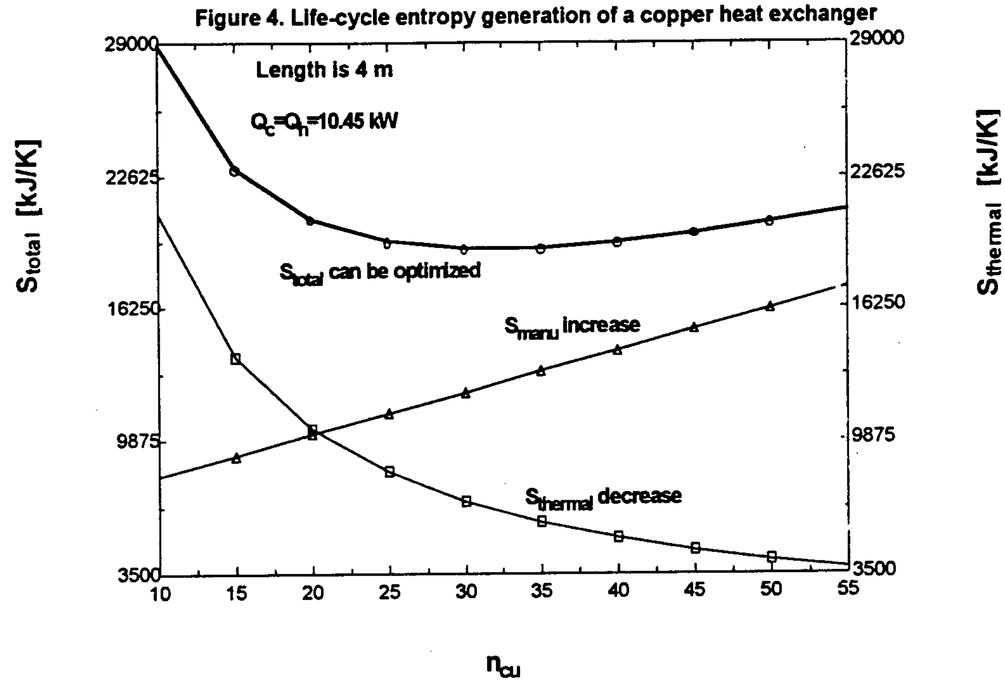


Figure 5. Optimization of the length of copper tubes

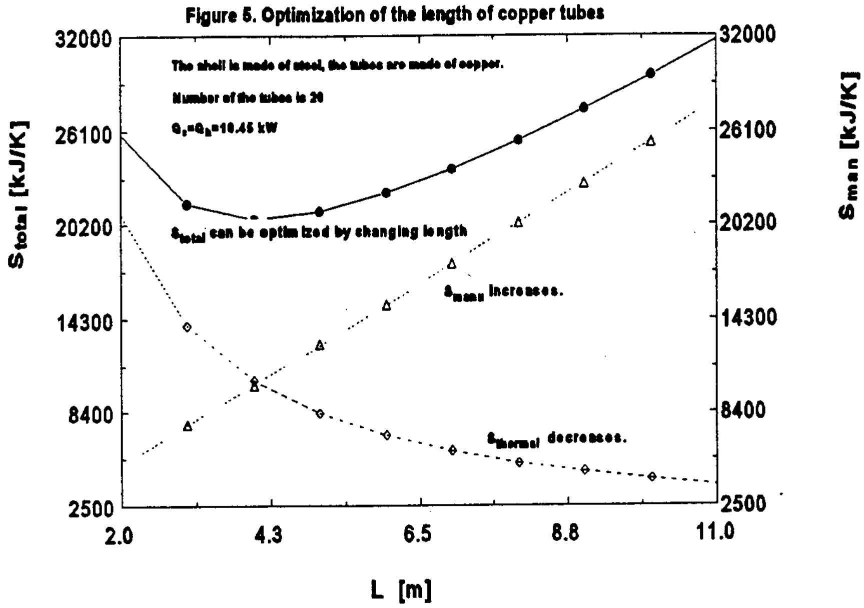


Figure 6. Optimization of the length of Aluminum tubes

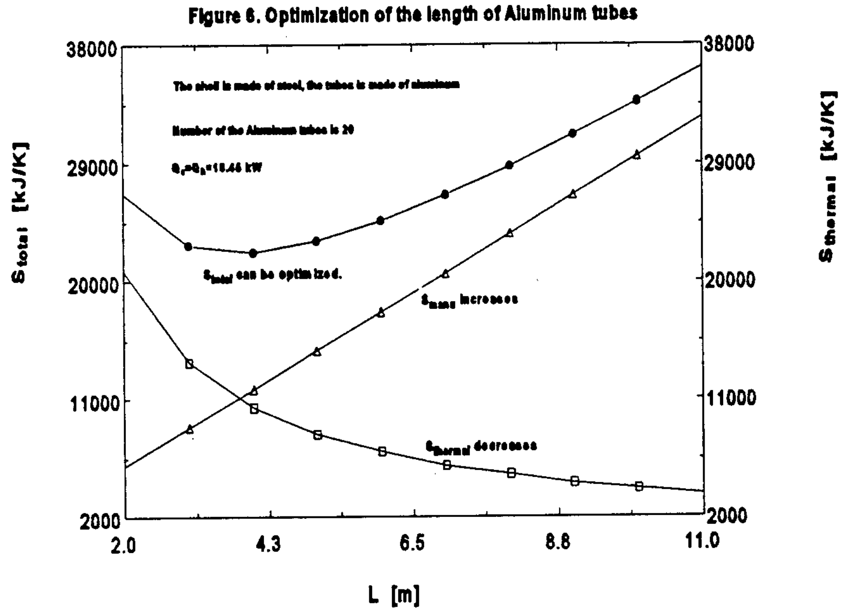


Figure 7. Optimization of the number of inside copper tubes

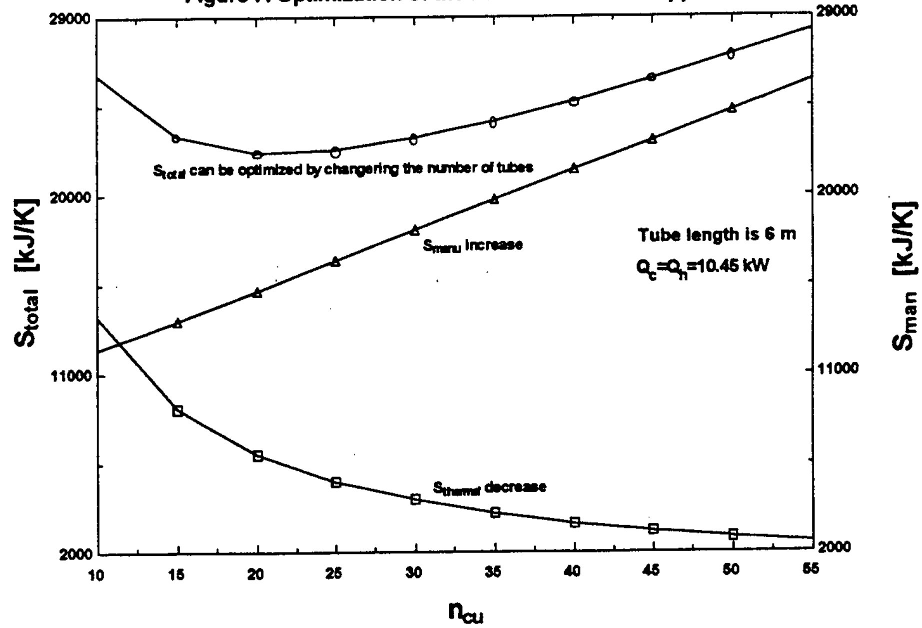
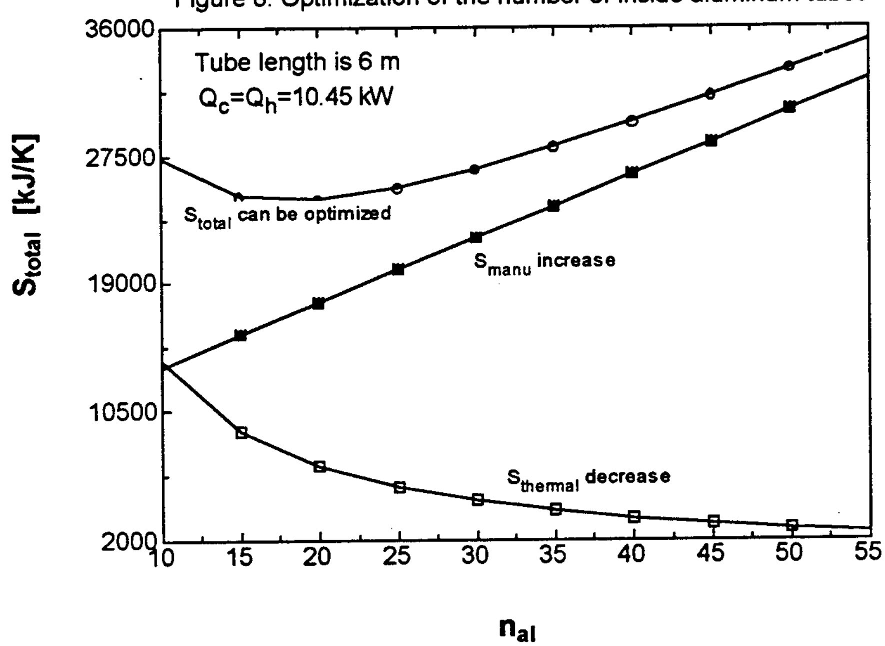


Figure 8. Optimization of the number of inside aluminum tubes



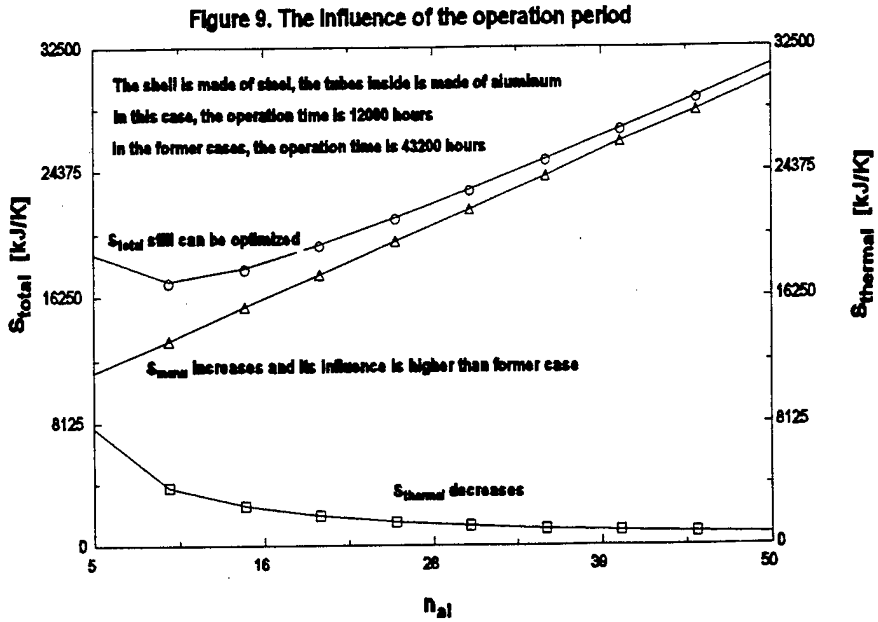


Figure 9. The influence of the operation period
The shell is made of steel, the tubes inside is made of aluminum
In this case, the operation time is 12000 hours
In the former cases, the operation time is 43200 hours
S_{total} still can be optimized
S_{manu} increases and its influence is higher than former case
$S_{thermal}$ decreases
S_{total} [kJ/K]
$S_{thermal}$ [kJ/K]
n_{al}
32500
24375
16250
8125
0
5
16
28
39
50

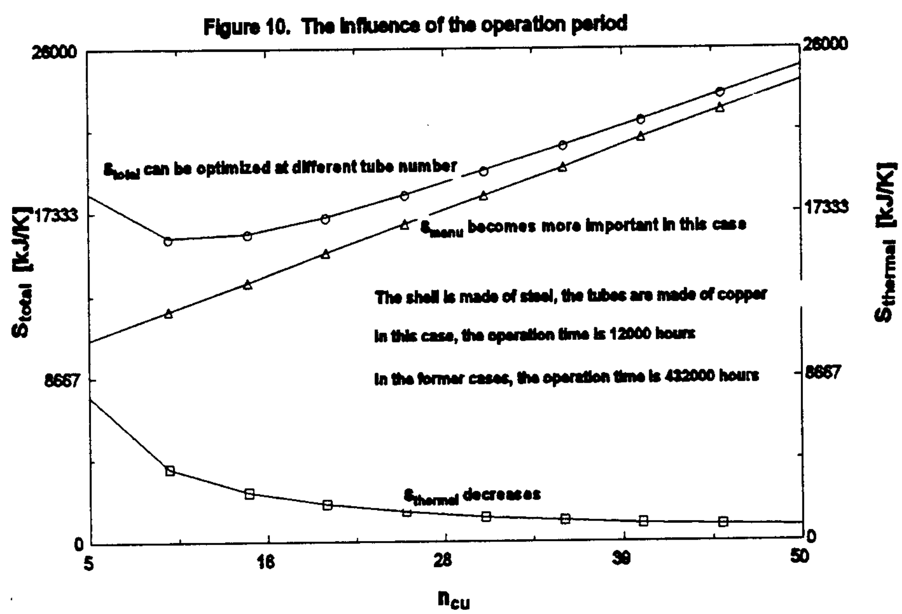


Figure 10. The influence of the operation period
S_{total} can be optimized at different tube number
S_{manu} becomes more important in this case
The shell is made of steel, the tubes are made of copper
In this case, the operation time is 12000 hours
In the former cases, the operation time is 432000 hours
$S_{thermal}$ decreases
S_{total} [kJ/K]
$S_{thermal}$ [kJ/K]
n_{cu}
26000
17333
8667
0
5
16
28
39
50

Discussion of the results :

All the following figures show the entropy generation on the y-axis. The x-axis shows the variables described below (heat exchanger length, number of tubes, etc.). The figures show three curves, entropy generation during operation, entropy generation during manufacturing process (both of opposite slope) and the sum of both, which always shows a minimum.

A. Discussion of the influence of length the heat exchanger (figure 5 and figure 6)

The length of the heat exchanger is treated as an objective function to be optimized both in the copper heat exchanger and aluminum heat exchanger. As shown in figure 5 and figure 6, the total entropy generation from the heat exchanger can be optimized by changing the length of heat exchanger. This phenomenon can be explained as follows: As the length of the tubes and shell increase, the total amount of the materials need to build the heat exchanger will increase too. Then the entropy generation from the manufacturing process (S_{manu}) will increase. At the same time, because the total heat transfer rate is constant, the extension of the heat exchanger will decrease the temperature difference between the two steams. This will reduce of the entropy generation during the operation process. The trends of these two change are reflected in figures 5 and 6. At a specific working condition, the graphs show that there is an optimal length to yield the minimum entropy generation during the life-cycle.

B. Discussion of the number of inside tubes (figure 7 and figure 8)

The second case is to study the number of the tubes inside the heat exchanger. The length of the heat exchanger is kept constant. The inside diameter of each tube is constant and the diameter of the shell is also kept constant. We try to explore how many tubes should be inserted to realize the entropy generation minimization during the life-cycle. When the number increases, the entropy generation from the manufacturing process increases too. At the same time, the heat transfer area between two steams will increase. Because of the total amount of the heat transfer will be kept constant, the temperature difference will decrease. This will cause the decrease of the entropy generation due to heat transfer contribution as we discussed before. The pressure drop between the tubes and shell will increase the cross-sectional area of the flow outside the tubes will decrease. In this case, the entropy generation from the temperature difference and the entropy generation from the flow friction are computed and added together as the entropy generation from the thermal process. This value is defined as $S_{thermal}$. The result shows that this value will decrease as the tube number increase. There is another restraint to the number of the inside tube. That is the space limitation. The number of tubes inside should have some upper limit. From figure 7 and figure 8, there also exist an optimal number of the tubes that can be inserted to minimize the entropy generation from the heat exchanger.

c. Discussion of the operation period (figure 9 and figure 10)

The operation time of the heat exchanger will influence the optimization process too. When the life time is changed (from 43200 hours to 12000 hours in this study), the optimal number of the inside tubes will also change. This is obvious because the portion of the

entropy generation from the thermal operation process will decrease by reducing the operation period. This is another factor that should be consider at the beginning of the design process.

Overall, the factors listed above are related to each other. The final design must include the consideration of all these factors. The results here clearly indicate that there is an optimum, the minimum entropy produced. However, the final selection can only be made when the proper penalties for weight and volume are also accounted for. This requires a complete system analysis. With the effort discussed here, the general ground work for such an analysis has been laid.

Chapter 5 Conclusion

A second-law analysis is conducted on a single-phase, counter-flow heat exchanger. This analysis is based on the concept of the entropy generation minimization during the entire life-cycle of the heat exchanger. The entropy generation during the material manufacture process is evaluated and included into the total entropy generation. In this study, the energy consumption of three commonly used metals are determined to be used in the entropy generation calculation. The other main contribution to the total entropy generation is entropy generation during the operation process over the life of the heat exchanger.

Based on this analysis, the following conclusion can be drawn:

1. After calculation and comparison, both of the two contributions mentioned above can influence the value of total entropy generation to a certain degree. During the design stage, both of these two factors should be considered.

2. The calculation of the entropy generation can be based on the 'entropy generation 'ratio calculated for the various energy conversion processes that contribute to the manufacturing and operation of the heat exchanger.

3. By comparing aluminum and copper as two alternative metals for the inside tubes in the heat exchanger, aluminum has the higher entropy production. Any weight savings come to bear only when the entire system is considered.

4. A series of the physical parameters, such as the diameter of the shell and the tubes, the length of the heat exchanger, the thickness of the shell and tubes, the operation period, etc. were considered and shown to influence the optimization result.

5. The working conditions of the heat exchanger, such as the temperature and pressure at inlet and outlet, will also influence the final result. Because the working conditions will change the entropy generation during the operation process.

6. All the entropy generation calculation are based exclusively on the energy conversion procedures. The other non-energy conversion factors, such as the capital investment, the recycle fee, are not included into the optimization process. But the mathematical model established in this study has already reflected the main contributions of the entropy generation during the life-cycle of the heat exchanger usage, so this study provides a reliable method to perform a thermal design based on the concept of minimum entropy generation.

7. The results here clearly indicate that there is an optimum, the minimum entropy produced. However, the final selection can only be made when the proper penalties for weight and volume are also accounted for. This requires a complete system analysis. With the effort discussed here, the general ground work for such an analysis has been laid.

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